Hypothesising the effects of Higgs portal dark matter in particle colliders

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Abstract. The Higgs field mass term in the Standard Model is unique. While all of the other interaction terms in the Standard Model are associated with strictly renormalisable dimension 4 operators (and therefore having marginal couplings), the Higgs field mass term has a coupling of dimension 2. This allows us to explore the possibility of the Higgs boson having decay channels consisting of particles being $SU(3) \times SU(2) \times U(1)$ singlets, meaning that they do not interact with any Standard Model particles apart from the Higgs. We could treat these particles as candidates in a field of study which is known as Higgs portal dark matter. In order to test this possibility, a model independent framework has been developed in the form of a Lagrangian consisting of extensions to the Standard Model: a heavy scalar H and a non-interacting dark matter candidate χ. The implications of this model are considered where a Monte Carlo study has been performed on the process $gg \to H \to h\chi\chi$ and hh. Applying this to ATLAS results for comparison with measured Higgs p_T, it is found that a good fit is found for the mass points $m_\chi = 60$ GeV and $m_H = 275$ GeV.

1. Opening the Higgs Portal

Up until this point, the Standard Model (SM) of particle physics has provided the most accurate prediction about the dynamics of elementary particles, by combining manifestations of QCD and Electroweak Yang-Mills theories [1, 2, 3, 4], most notably using the Higgs mechanism [5]. There are, however, obvious shortcomings in the SM. In particular, it is well understood that there are no SM particles which are viable dark matter (DM) candidates – that is, SM particles are all *visible* in that we have the means to detect them directly. The compelling astrophysical evidence for the existence of DM has yet to be explained by a convincing argument in particle physics terms.

In the literature, one can find a plethora of hypotheses with the intention of presenting a theoretically motivated DM candidate as a particle (for a thorough review, see reference [6]). While most of these hypotheses are model dependent, this study presents a framework for a DM candidate which is based on a small class of DM models called *Higgs portal* models [7, 8, 9], which can largely be explained without having to resort to some higher theoretical explanation.

Higgs portal models, examples of which were first comprehensively presented by Brian Patt and Frank Wilczek [10], essentially make use of the Higgs boson's unique coupling to massive particles in order to motivate the possible existence of states which do not interact with SM particles. The Higgs term in the SM Lagrangian is unique in that it does not contain a marginal (or dimensionless) coupling. While all of the other interaction terms contain dimension 4 operators (and therefore marginal couplings), the Higgs term has an operator with dimension 2 forcing its coupling, μ^2, to have dimension 2 also. This means that we could allow the Higgs field to couple to new fields which are SM $SU(3) \times SU(2) \times U(1)$ singlets. SM singlets will not interact with SM particles at all, giving the possibility to add DM candidates[1] which interact only through the Higgs boson.

A key example of a Higgs portal model is that of a complex scalar singlet extension to the SM (CxSM) [7]. The basic idea is that a CxSM adds two new massive scalar degrees of freedom to the SM. One might be thought of as a new scalar boson which interacts with the SM similarly to the Higgs boson, and the other could be thought of as a DM candidate. While there is plenty of rich phenomenology linked to this model (most of which can be found in reference [7]), I only mention this example as a theoretical case study for the framework described below.

2. A Minimal Extension to the Standard Model

In this study we do not consider a theoretical construction of a DM model, but a framework containing two new particles. This is experimentally motivated, since we see experimental results which could be explained most simply be introducing two new particles (this will be elaborated on in the following section).

Firstly, we introduce a Higgs-like boson, which interacts with SM particles in the same way as the Higgs boson and is a CP even scalar, but has a larger mass than the SM Higgs boson, similar to the extra CP-even component introduced when using a 2HDM [11]. We denote this particle by an upper case H, and it is not to be confused with the SM Higgs boson, which we denote by a lower case h.

In addition to this, we introduce a scalar DM candidate denoted by χ. We do not specify any theoretical motivation for χ except that it could come from a model similar to the CxSM described above. In this case, DM denotes any particle which could not be directly observed in a detector, but only be detected through a mismatch in conservation of momentum.

Due to the simplistic nature of this framework, we can very easily write down the Lagrangian for a theory involving these two particles. It would be a completely independent sector from the SM Lagrangian, such that we could write,

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\text{BSM}}, \tag{1}$$

where $\mathscr{L}_{\text{BSM}}$ specifies the beyond SM (BSM) additions made to the SM. The BSM sector specifies interactions between h, H, and χ particles as follows:

$$\mathscr{L}_{\text{BSM}} = \mathscr{L}_{\text{K}} + \mathscr{L}_{\text{T}} + \mathscr{L}_{\text{Q}} + \mathscr{L}_{Hgg} + \mathscr{L}_{HVV} + \mathscr{L}_{\text{Y}}, \tag{2}$$

where we have kinetic terms, trilinear interactions, quartic interactions, an effective H to gluon-gluon interaction, a tree level H coupling to the weak bosons V (where V is either Z or $W^{\pm}$), and a Yukawa interaction for H, respectively. These interaction terms could also be found in a typical SM Higgs Lagrangian, barring the coupling to DM.

Omitting the obvious nature of the kinetic term, the form of the other terms are constructed

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[1] Brian Patt and Frank Wilczek first referred to this as *phantom matter*, since the term dark matter was only used in an astrophysical context. These days, particle physicists tend to refer to any field which doesn't interact with the SM as dark matter.

as follows [12]:

$$\mathscr{L}_{\mathrm{T}} = -\frac{1}{2}\lambda_{_{Hhh}} Hhh - \frac{1}{2}\lambda_{_{h\chi\chi}} h\chi\chi - \frac{1}{2}\lambda_{_{H\chi\chi}} H\chi\chi, \tag{3}$$

$$\mathscr{L}_{\mathrm{Q}} = -\frac{1}{4}\lambda_{_{HHhh}} H^2h^2 - \frac{1}{4}\lambda_{_{hh\chi\chi}} h^2\chi^2 - \frac{1}{4}\lambda_{_{HH\chi\chi}} H^2\chi^2 - \frac{1}{2}\lambda_{_{Hh\chi\chi}} Hh\chi^2, \tag{4}$$

$$\mathscr{L}_{Hgg} = -\frac{1}{4}\beta_g\ \kappa_{hgg}^{\mathrm{SM}} G_{\mu\nu}G^{\mu\nu}H, \tag{5}$$

$$\mathscr{L}_{HVV} = \beta_V \kappa_{hVV}^{\mathrm{SM}}\ V_\mu V^\mu H, \tag{6}$$

$$\mathscr{L}_{\mathrm{Y}} = -\frac{1}{\sqrt{2}} y_{_{ttH}} \bar{t}tH - \frac{1}{\sqrt{2}} y_{_{bbH}} \bar{b}bH. \tag{7}$$

Other relevant parameters in this framework which appear in the kinetic part of the Lagrangian are m_H and m_χ, the masses of the heavy scalar and the DM candidate, respectively.

While this framework contains a large number of parameters, in practice we are able to fix enough of these to leave just one free parameter. This free parameter is β_g, which is present in equation 5. The practical relevance of this framework is discussed in the following section.

3. Application to LHC Physics

It might be unclear thus far as to what motivation there is for introducing a DM candidate and a heavy scalar, as additional particles to the SM. From an astrophysics point of view, it is obvious that the SM is incomplete and is in need of an extension to explain the DM relic density in the Universe. But more recently, results from the ATLAS and CMS collaborations based at CERN have presented tantalising results which motivate the existence of new particles.

Recent results for di-Higgs resonances have shown excesses in decays coming from double Higgs production. In particular, ATLAS has presented an exciting study in $hh \to \gamma\gamma b\bar{b}$ decays [13] which promotes the possibility of the discovery of a heavy CP even scalar having a mass around 300 GeV. In fact, a few other studies (including some by CMS) also appear to show resonances with a mass between 270 and 300 GeV. These excesses are the motivation for postulating the existence of a heavy scalar.

In addition to this, ATLAS has also released a set of analyses containing kinematic information from Higgs production using only events which are confined to a particular phase space – the so-called fiducial regions. The effect of this is essentially to remove any experimental bias from the results. This has been done comprehensively for both the $h \to \gamma\gamma$ [14] and $h \to ZZ^* \to 4\ell$ [15] decay channels.[2] When we consider the Higgs p_T spectra in these analyses we discover that the current SM prediction does not accurately reproduce the experimental data. Instead, we see an excess of p_T in the region between 20 and 100 GeV (the intermediate region). This boosted p_T could be explained by the Higgs boson recoiling off of a DM candidate.

It is natural, then, to ask if adding these two particles can affect the kinematics of produced Higgs bosons to such an extent that the discrepancies in the data can be explained. To test this question, Monte Carlo simulations were done using `MadGraph 5` [17] based on a model build from the Lagrangian in equation 2 using the Mathematica package `FeynRules` [18]. We generated events using proton-proton collisions having a final state of $h\chi\chi$. The reason for this is to ensure the stability of DM particles. Since a Higgs boson might decay into a pair of χ particles, their mass must be smaller than $m_h/2$. Kinematically, then, we would get a large cross

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[2] ATLAS have also released a paper reviewing the combination of both the $\gamma\gamma$ and $ZZ^* \to 4\ell$ decays [16], although we did not use the combination to obtain results, due to the methods they used in combining the two decays. Having said this, the results we obtained would not have been significantly different if we had used the combination study.

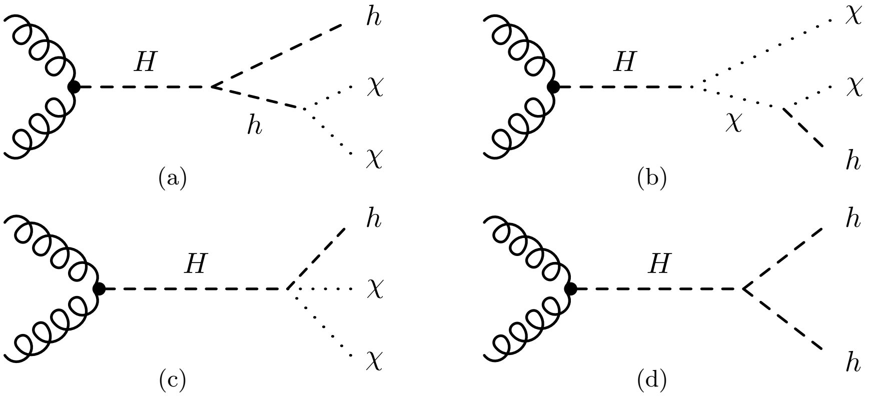

Figure 1. The three dominant Feynman diagrams contributing to Higgs production in proton-proton collisions, when an H s-channel is required. The production of $h\chi\chi$ (a, b, and c) and hh (d) both impart boosted transverse momentum to the produced Higgs bosons.

section contribution from $h\chi\chi$ production[3] (as opposed to $h\chi$ production). The production of hh was also simulated, although this is a small effect compared to $h\chi\chi$ production. These final states were assumed to be dominantly produced through an s-channel H resonance such that the relevant Feynman diagrams which were used for the calculation are those shown in figure 1 – this assumption was checked and shown to be valid.

As can be seen from the diagrams in figure 1, the only relevant couplings which needed to be fixed were λ_{Hhh}, $\lambda_{h\chi\chi}$, $\lambda_{H\chi\chi}$ and $\lambda_{Hh\chi\chi}$. The first coupling, λ_{Hhh}, was fixed by picking a conservative production cross section for $H \to hh$ of 2 pb, coming from the study in reference [13]. The parameters $\lambda_{h\chi\chi}$ and $\lambda_{H\chi\chi}$ were fixed using astrophysical observations, using both the DM relic density [20] and the DM-nuclei inelastic scattering cross sections determined by the LUX experiment [21]. The mass points selected for H and χ were based on experimental indications, and were set at $m_\chi \in \{40, 50, 55, 60\}$ GeV and $m_H \in \{275, 285, 300\}$ GeV. Finally, the coupling $\lambda_{Hh\chi\chi}$ was scanned over by considering three different values for the branching ratio of $H \to h\chi\chi$, those being 50%, 60%, and 70%.

Having fixed all of the relevant parameters relating to the interactions between h, H and χ, the only relevant parameter left free was β_g. Since β_g affects the contributions of all of the diagrams in equal proportion, it was used as a free parameter to fit the model to the ATLAS experimental results in references [14] and [15]. By doing a simultaneous fit for both the $\gamma\gamma$ and $ZZ^* \to 4\ell$ Higgs p_T distributions, we were able to obtain the best fit by setting $m_\chi = 60$ GeV, $m_H = 275$ GeV and $\text{BR}(H \to h\chi\chi) = 60\%$. The best fit (which was obtained by minimising χ^2 over the number of degrees of freedom, $n.d.f$) required a β_g value of 2.07±0.37. It should be noted that the SM prediction does not accurately describe the data, having a $\chi^2/n.d.f$ of 1.59. Using our model with the mass points we have proposed, we are able to reduce this to 0.86, giving a much better fit to the data. For a detailed description of a number of results, the reader is encouraged to look in reference [12].

4. Concluding Remarks

The framework presented is attractive for two obvious reasons. Firstly, it does a very good job at explaining discrepancies which we see in the ATLAS experimental Higgs data. There is a clear correlation between the discrepancies in the data from the $\gamma\gamma$ and the $ZZ^* \to 4\ell$ channels, both

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[3] A similar production mechanism has been considered in mono-Higgs searches [19], although without an explicit interest in the importance of hh production.

of which can be explained by the Higgs boson recoiling off of undetected particles. Secondly, the framework is attractive due to the fact that it very elegantly explains two experimental excesses simultaneously. While ATLAS data points to the excess mentioned above, the framework also explains excesses in di-Higgs resonances which are seen by both CMS and ATLAS.

While this short paper has highlighted the explanation of a few experimental results, one could ask what predictions the framework makes and what signatures to be mindful of for future experimental efforts. A possible prediction can be made if equations 6 and 7 are considered. I have not yet made mention of the possible weak boson or jet production mechanisms arising from the addition of the proposed framework. If we assume that the HVV coupling is small, then the possibility for top quark production is not so highly suppressed by the negative interference from the HWW coupling (we see this suppression in the SM). This means that top quark production should occur at a much higher rate than what is predicted by just the SM. In fact, an excess in top quark production has been observed, albeit a small one.

The framework presented is a tantalising and exciting tool to be used for the exploration of new physics at the LHC. While good results are presented in this short paper, it is imperative that more experimental data be accrued in order to clear up any statistical fluctuations. With Run 2 of the LHC currently under-way at the time of writing this paper, we can expect a far more thorough and meaningful analysis to take place in the near future.

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